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Wireless technology and satellite internet access for high-speed whole farm connectivity in precision agriculture ☆

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Abstract

An analysis of the multispectral image-based precision agriculture technology as used in the US cotton belt was undertaken to identify bottlenecks which limit the delivery and use of this technology. One area in particular was identified: the movement of data and information necessary to implement variable rate applications. Solutions to reduce or eliminate this problem were explored. A new technology called wireless local area networking (or WLAN) was explored. A test farm was selected, a system was designed and implemented, and the resulting implementation was successfully tested. The system wirelessly connected cotton pickers, spray equipment, variable rate fertilized application equipment, and hand-held personal digital assistant computers in the field, allowing for rapid bi-directional movement of data and information.

Keywords: Wireless; Networking; Internet; Precision agriculture; Multispectral image

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1. Introduction

In taking an analytic approach to examine the entire process of remote sensing, image analysis, variable rate prescription generation, on-farm data capture, data and image archival, and information transfer to and from the farm, several bottlenecks are immediately observable. When using satellite collected images, the time from image collection to delivery of the raw image data is too long for practical use in realtime precision agriculture applications. Processing of remotely sensed images so that they can be used in geographic information systems (GIS) such as ARC-View [1] and image analysis software such as Imagine or ENVI is a time consuming process. The use of fixed wing aircraft for image data collection currently promises to shorten the delivery time to acceptable margins. As technology improves and the need for commercial providers of image capture and image analysis grows, it is likely that the market place will provide some answers to this bottleneck.

A second area of concern is data communication capability between rural farms and the sites where image analysis and prescription generation occurs. While some farms will have their own capability to perform image analysis and variable rate prescription generation, most growers will choose to have this done by consulting organizations. Even so, the former group will still be delayed in delivering prescriptions to application machinery by having to hand-carry media. Thus, there are two communication problems to address: (1) remote, high-speed communications between the farm and service providers and (2) local area networking on the farm.

2. Analysis of the communications problem

Currently one of the solutions for data communications between rural farms and service providers in the US cotton belt is the telephone system and high speed modems. The physical limit of modem technology using copper lines is 56 Kbps. The quality of local telephone lines, the central switching systems, and the lines between the two switching systems govern the actual speed which the modem can carry, often much less than the top speed. If the farm happens to be within 18,000 feet of the local central switching system, in the near future access to DSL (digital subscriber line) technology may be available which can operate at 1.5 Mbps bidirectionally. However, since most farms in the US are located further than 5500 m from the local switching center, DSL is not an option. Currently, there is only one commercial alternative to obtain high-speed data communication economically, and that is the use of satellite technology.

The second side of the communications bottleneck is the provision of local area network capability for the entire farm. Since tractors, pickers, spray equipment, combines, and center pivot irrigation systems move, this precludes the use of wireline

[1] The use of trade or product names is for information only and does not imply a recommendation or endorsement of the USDA-ARS.

systems with maybe the exception of the center pivot system. The possible solution to this problem is the use of wireless local area network technology. The Federal Communications Commission in the US has set aside three bands of frequencies in 1985 via Rule 15.247 (Code of Federal Regulations, 1985) for public use for which no license is required (Geier, 2002). The first band to become available was the 2.4 GHz ISM (industrial, scientific, and medical) band which actually ranges from 2.400 to 2.485 GHz, a total of 85 MHz. However, there are restrictions on the use of this band. The total power transmitted must not exceed 1 W of radiated power, and the bandwidth was divided up into discrete bands, which must be accessed by spread spectrum technology. This assured that multiple users could have access in the same area, but at the same time the first users were assured by FCC rule that they had priority and subsequent users must not interfere with prior users. By limiting the transmission power, the range, or size, of each cell, much like cellular telephone technology, was limited to approximately 2 miles line-of-sight using an omni-directional antenna at the base station. For a more detailed discussion of this technology and the other public bands available, see Geier (2002), Ibe (2002), and Reid (2001).

3. High speed satellite internet service for farms

To make the use of precision agriculture methodology available and transparent to the grower, there needs to be a high speed data path from the grower's farm to the service provider. Today, large data or image files have to be hand carried from the image analyst to the farm. Most commercial variable rate controllers use multi-megabyte PCMCIA memory cards for this function. Typically image files range in the multi-megabyte size, making data transmission via telephone modem impractical; first, by the length of transmission time required, and second, by the likelihood of errors to occur in lengthy transmissions causing multiple retries. So, if hand carrying is unacceptable because of travel time and media problems and if telephone modem is also unacceptable, where can we turn? In the fall of 2000, high speed Internet access became available in low cost equipment and service through Starband Communications, Inc. via the Dish Network, Inc. fixed satellite system. A competitive satellite Internet access service is also available from Direct TV, Inc., called DirecWay, which has comparable pricing and speeds available for both residential and commercial use.

To test the capabilities of the satellite system, a subscription service was established and equipment procured from DirecWay, Inc. for the Paul Good Farm located in Noxubee County, MS, USA, a research cooperator. The satellite dish (approximately 1 m in diameter), two way amplifiers and the modem box cost about \$500, including professional installation which is mandatory. The monthly subscription service for Basic Business service which includes a permanent Internet address is \$89.99. The connection between the base computer and the satellite transceiver is via a USB port.

The data transmission rate minimums for the system are 500 Kbps downlink and 75 Kbps uplink. Actual downlink data rates have been observed, using the systems monitoring software, exceeding 1000 Kbps. Maximum uplink speed is 150 Kbps with typical speeds from 75 to 100 Kbps.

4. Justification for delivering high technology to mainstream customers

Multispectral imaging collected with cameras mounted on fixed-wing aircraft is useful in precision agriculture to determine soil types, crop health, soil moisture, crop nutrient status, and crop termination. When used with crop yield maps generated from yield monitors in combination with global positioning system (GPS) sensors, field images become even more valuable. One of the most useful manipulations is the creation of a normalized difference vegetation index (NDVI) which is defined as the ratio of the difference of the near infrared (NIR) and the red data divided by the sum of the NIR and the red data on a pixel by pixel basis for the entire image (Schowengerdt, 1997). The NDVI map properly classified shows areas of a field which are strongly growing versus areas which are growing at a relatively slower rate. We have used NDVI images to determine areas where insect scouts should find early season populations of insect pests versus poorer growing areas of the field where there should be no pests. Subsequent maps are then developed to apply pesticides on a spatially variable application basis. Using these application maps, only areas of the field where insects have been found are sprayed. The relatively poorer growing areas of the field are not sprayed, resulting in a possible 60% reduction on an annual basis of pesticide application.

Using multispectral images, NDVI images and application maps is very high technology typically beyond the capability of most growers and agricultural consultants. This requires the use of geographic information system (GIS) and image analysis software products such as ERDAS Imagine, ESRI ArcView, Research Systems' ENVI, and SST Corp.'s SSToolbox. Desktop computers with a minimum of 256 MB of memory and 10's of gigabytes of storage are used to process the images to obtain the application maps used in multiple operations in precision agriculture: (1) variable rate seeding, (2) variable rate fertilization, (3) variable rate irrigation, (4) variable rate plant growth regulator application, (4) spatially variable insecticide application, and (5) variable rate herbicide application. All of the operations with even fairly small cotton fields, involve data files which consist of megabytes to gigabytes of data. The application maps themselves are not small, usually a few megabytes in size per field.

As precision agriculture becomes a commercial operation in cotton, the typical grower will most likely not deal with image collection, image processing, or evaluation of application maps generated thereof. Instead, these processes will be handled by precision agriculture specialists who have training in image analysis and the use of software systems mentioned above. It is important that these personnel also have training in production agriculture so that they can readily communicate with growers and agriculture consultants to whom they will deliver their products. Most farm operations then will not have these personnel onsite. This means that a form of high speed digital communication between the farmstead and the image analysis shop has to exist or the time constraints between collection of image data, image analysis, ground truthing by the farmer or consultant, and delivery of final application maps to the application machinery could easily be exceeded.

As an example of what can happen on a large farming operation, in 2001 $1\frac{1}{2}$ h were required to collect and $1\frac{1}{2}$ h were required per day to deliver PC cards which held as-applied maps and application maps, respectively, to multiple machines spread out over 20 km and 5000 ha.

Scientists in our group examined the current entire precision agriculture system for cotton production as it exists today in the Mid South Region of the US. The most severe time constraint involves a new technology for cotton insect control. With the advent of BT cottons and the advance of the Boll Weevil Eradication program, growers no longer have much concern about controlling boll weevil (*Anthonmous grandis*) or the *Heliothis zea* and *Heliothis virescens* worm complex. Since nature abhors a vacuum, one of the insect species that has now become a major pest is the tarnished plant bug (Turnipseed et al., 2002). One of the authors, Dr. Jeffrey Willers, has developed a methodology using multispectral imaging as its basis for developing a spatially variable insecticide application map for early season control of this pest. The time threshold from image acquisition to actual control spray should not exceed 48 h. One of the major bottlenecks in processing the aerial image was first spatially registering all of the bands of each image and then mosaicing these images to obtain a single image of the entire field or farm of interest. However, since this project was undertaken, private industry has now solved this problem which used to take 3–6 h, depending on complexity. Now as soon as the plane lands and about 15 min of processing, a completely spatially registered image, which is already mosaiced for the area of interest, can be delivered via high speed Internet for immediate image analysis. Two major problems still remain. The process of image analysis needs to be automated. We believe that on a farm by farm basis this can be accomplished. The final problem consists of providing for two-way, high speed communication between the image analyst and the farm operation.

Since image analysis for most growers will be handled remotely from the farm operation, high-speed digital communication is mandatory. With this avenue open, everything becomes possible. It will not matter where the image analysis operation is located as long as it is competent, timely, and cost effective. This communication must be bidirectional, but the uplink need not be as fast as the downlink. A fast downlink is mandatory when delivering files which are megabytes in size. When (NDVI) or NDVI-like maps are used with the technology developed by Dr. Willers, these must be delivered as soon as possible to the agricultural consultant on the farm. The consultant will then use this image as a guide to rapidly, effectively, and precisely scout the farm for occurrence and non-occurrence of insect pests. Once confirmed, the scouting information is then transmitted back to the image analyst for creation of the insecticide application map. If additional areas are deemed to be sprayed by the consultant beside the ones indicated by the NDVI map, then this information must be captured locally and transmitted back to the image analyst for incorporation into the generated application map. As soon as the application map is generated, this map must be sent to both the grower and the consultant for their approval or markup. Our research experience with consultants and growers lead us to strongly believe that these people must be included in the decision making loop for the recommendation to be readily accepted. The resulting map is then sent back to the analyst for final markup and generation for the appropriate controller on the spray equipment. All of these steps must be made as rapidly and as painlessly as possible for the grower and consultant.

5. A WLAN for the farm

A solution to some of the information bottlenecks which hinder the application of precision agriculture in cotton production is to implement a wireless local area network (WLAN), which can connect all of the grower's operations and machinery. The grower also needs the option of installing equipment incrementally. Since tractors, pickers, sprayers, spreaders, and combines move in the field, the WLAN must have the capability to service moving equipment. One such WLAN system is the BreezeCOM, Inc. (now called Alvarion, Inc.) BreezeNET PRO.11 Series and the BreezeACCESS II Series of equipment. Scientists and technicians in our group worked with personnel of Star-Net Communications, Inc. of Knoxville, TN, an engineering and sales representative of Alvarion, Inc., in designing a wireless local area network system for the Paul Good Farm of Noxubee County, MS, USA, a research cooperator. The Good has approximately 610 ha of contiguous land area under cultivation. The WLAN coverage map for the Good Farm using the base station and three repeater stations broadcasting inward to the farm is shown in Fig. 1. The base-station radio equipment, satellite Internet equipment, and computer workstation was located in the farm central office. The bidirectional satellite Internet dish antenna was mounted on the roof of the office building. A list of all the equipment used, and the settings for the wireless local area network are presented in Table 1. Since radios which work at the 2.4 GHz microwave range function *strictly* on a line-of-sight (LOS) basis, the base station antenna array was placed on top of the highest structure at the farmstead. The base station uses an omni-directional antenna while the repeater stations use a high gain directional antenna to communicate with the base station and a 180° sectorial antenna.

While the base station is powered using available 110 VAC source at the farm office, two for the repeater stations did not have 110 VAC for a power source. They were designed to use slow discharge batteries for an overnight energy source and a solar panel array as a 12 VDC source during the daytime. The solar array during the daytime had a sufficient surplus of energy to recharge the battery and to supply the two radios concurrently. Two different DC voltages are required for the radios. One requires a 12 VDC source while the other requires 5 VDC supplied through a 12 VDC to 5 VDC converter. All equipment mounted outside was contained in a NEMA 4 weatherproof metal box.

Two types of systems were designed for mobile operations. Since many precision agriculture operations involve the transference of application maps from the farm central computer (or via satellite Internet from the image processing site) to the con-

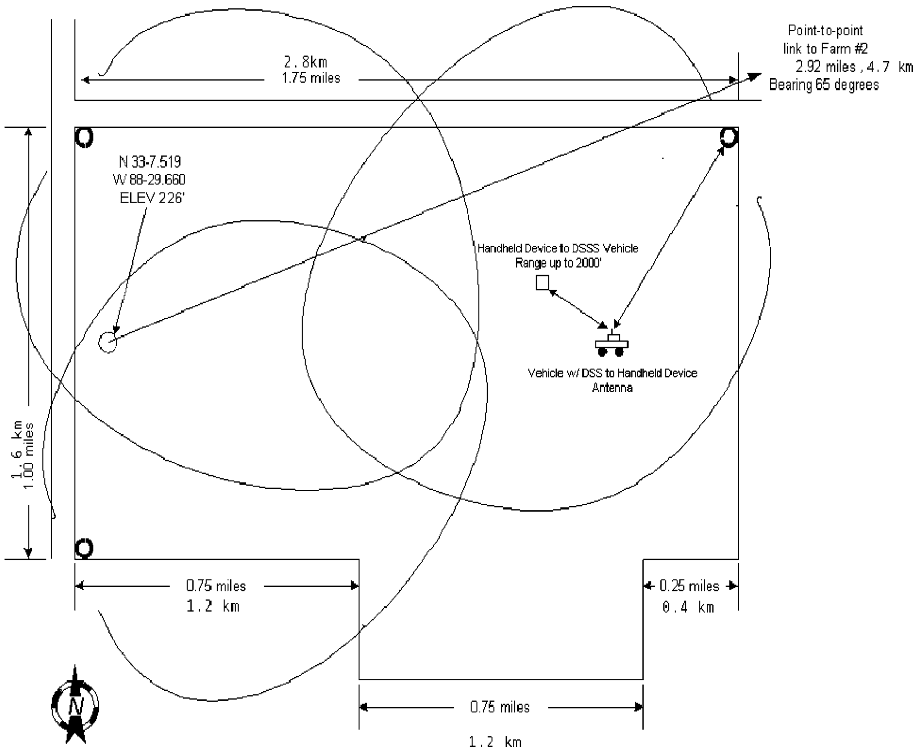

Fig. 1. Coverage of the Good Farm using repeater stations as basis for the wireless local area network and base station to provide connectivity to the base computer and satellite Internet.

troller mounted in the cab of the appropriate farm machinery, we undertook designing the first component of the WLAN that would allow direct transfer to the computer controlling the variable rate equipment even while the equipment was in motion and in use. Any variable rate controller system which can use a Windows CE, 95, 98, 2000, or NT based computer with a RJ45 Internet port will work. An important feature of the BreezeCom radio equipment is the capability to provide a continuous high speed data link while in motion at speeds up to 80 kph with automatic transfer from cell to cell within the coverage area. Thus, not only can we provide downloads of new, additional variable rate application maps for fields as they are generated, we can also monitor in real-time the actual application of materials to the field and equipment location and performance with suitable sensors connected to the computer.

The second mobile system we designed is used to provide for communications to the farm consultant and to Dr. Willers while they are in the field conducting scouting operations. The equipment was mounted in a NEMA 4 environment-proof box which resided in the scouting vehicle with two magnetic mount antenna located on the roof of the vehicle. Power was supplied by the vehicle battery to the radios

Table 1
List and description of equipment used for implementation of the wireless local area network

Equipment type	ESSID	IP Address	Name	Location	Antenna type	FH or DS	DS channel	Hopping sequence	Hopping set
BreezeACCESS II AU-E-BS	MSU-AirBA	10.0.0.15	MSU-15	Base Station	8 dBi Omni	FH	NA	5	1
BreezeNet DS.11- BU	MSU-AirDS	10.0.0.55	MSU-55	Base Station	8 dBi Omni	DS	6	NA	NA
BreezeACCESS II SU-A-BD	MSU-AirBA	10.0.0.10	MSU-10	Repeater 1	16 dBi Integrated Directiional	FH	NA	5	1
BreezeNet Pro.11 AP-10D	MSU-AirNet	10.0.0.50	MSU-50	Repeater 1	17.5 dBi Til-Tec Directional	FH	NA	10	1
BreezeACCESS II SU-A-BD	MSU-AirBA	10.0.0.11	MSU-11	Repeater 2	16 dBi Integrated Directiional	FH	NA	5	1
BreezeNet Pro.11 AP-10D	MSU-AirNet	10.0.0.51	MSU-51	Repeater 2	17.5 dBi Til-Tec Directional	FH	NA	11	1
BreezeACCESS II SU-A-BD	MSU-AirBA	10.0.0.12	MSU-12	Repeater 3	16 dBi Integrated Directiional	FH	NA	5	1
BreezeNet Pro.11 AP-10D	MSU-AirNet	10.0.0.52	MSU-52	Repeater 3	17.5 dBi Til-Tec Directional	FH	NA	12	1
BreezeNet Pro.11 SA-10	MSU-AirNet	10.0.0.53	MSU-53	Vehicle 1	8 Dbi Omni	FH	NA	Mobile	NA
BreezeNet DS.11-BU	MSU-AirNet	10.0.0.13	MSU-13	Vehicle 1	8 Dbi Omni	DS	6	NA	NA
BreezeNet Pro.11 SA-10	MSU-AirNet	10.0.0.54	MSU-54	Vehicle 2	8 Dbi Omni	FH	NA	Mobile	NA
BreezeNet DS.11-BU	MSU-AirNet	10.0.0.14	MSU-14	Vehicle 2	8 Dbi Omni	DS	6	NA	NA
BreeseNet Pro.11 SA-10	MSU-AirNet	10.0.0.56	MSU-56	Tractor 1	8 dBi Omni	FH	NA	Mobile	NA
BreeseNet Pro.11 SA-10	MSU-AirNet	10.0.0.57	MSU-57	Tractor 1	8 dBi Omni	FH	NA	Mobile	NA

FH is for frequency hopping radios, DS is for direct sequence radios, ESSID is the network name of the radio. All radio equipment is made by Alvarion, Inc. All radios have private Internet protocol (IP) addresses as indicated. FH radios use all 79 one MHz channels of the 2.4GHz band and are assigned the indicated hopping sets and sequences which allow them to communicated with each other in a non-interferring manner. The DS radios have 11 channels in which to operate. However, only channels 1, 6 and 11 which are each 22 MHz wide are independent and do not overlap. We chose to use channel 6 because it is the most unused channel in this 2.4 GHz band. We were able to use both FH and DS in this system with minimum self-interference.

and laptop computer via 12 VDC to 110 VAC inverter. The scout can communicate bidirectionally to the farm central computer, his own computer located at his office via the Internet or to the image analyst computer via the Internet by the WLAN. He can even download or upload files while driving on the farm, saving time. As the scout exits the vehicle, communication is maintained by using a ruggedized Windows CE personal digital assistant (PDA) hand-held computer, ie. IPAQ 3640. This computer was equipped with DSSS radio, a GPS sensor for navigation and spatial registration of collected data, and GIS display software such as ESRI's ArcPad 6.0. While having sufficient memory to handle single image display and recording a single day's worth of scouting information, the computer's battery system allows for active operation for 5–6 h. More memory could be added to allow for storage of more images for scouting purposes but this would result in much more expense and significantly less run time. By having a WLAN connection, images can be rapidly downloaded minimizing cost and maximizing operating time. This equipment array allows the scout to use images which are spatially registered to navigate to sites of interest to collect ground truth data that confirm the presence or absence of insect pests. This collected data is spatially and time stamped using the GPS sensor. The scout can send this data at high speed while he is still in the field back to the image analyst located remotely from the farm operation. Furthermore, as the scout is walking back to his vehicle, he can begin downloading, at high speed, the next GIS field image he will scout, again saving time. As this data is transmitted from the scout's hand held computer, it can be archived on the laptop in the cab, it can be archived at the farm central computer, it can be archived at the scout's home office computer, and finally it can be archived at the image analyst's office computer, since all are connected to the WLAN and/or the Internet. We have used this system for two years in successfully downloading images for scouting and for recording the scouting results. Care must be taken to not exceed the battery operation time or loss of data could occur. We maintained a practice of transmitting each field's information after collection to ensure no loss of data after running in to the "battery-down" problem. As long as the PDA is in range of the scout vehicle (less than 500 m), communication is maintained.

6. Variable rate controllers

One of the computer controllers we are testing this year is the ZYNX controller supplied by Micro-Trak Systems, Inc. The ZYNX is a Windows 98 based computer with a touch-sensitive screen which connects to all industry variable rate controllers currently in use. The rear panel of the controller has multiple connections available which include 4 RS-232 serial ports, 2 DB-25 parallel ports, one recessed USB port, one flush mount USB port, one external VGA monitor port, one keyboard port, one mouse port, one RJ-45 ethernet LAN port, and one CANBUS port. The ethernet port allows for direct connection to the WLAN radio. Since the Zynx controller is a Windows 98 computer, drivers already exist which facilitate communication via the WLAN. Thus, precision application maps can readily be downloaded into the computer from the base station computer or more remotely from the developer of the application map via the Internet, wherever that person is physically located, totally obviating the need to generate application maps on PC cards and hand carrying these cards to the machine controller. For smaller farms this may not seem important, but for the larger commercial farms this capability may mean the difference between meeting time critical applications within the allocated deadline time frame or having to start the entire process over again because the parameters have changed too much. An example is the early season application of a spatially variable insecticide for insect control. One of the authors, Dr. Willers, has shown in his research that by using NDVI maps for developing a spatially variable application map, with ground truthing, insect control in cotton can be obtained by using as little as 40% of the materials used in conventional blanket spray applications. However, this holds true only if the spatially variable spray is applied, maximally, within 24 h from the time the multispectral image was acquired. This time can be extended to 48 h, and the spray will still be effective. Any time beyond 48 h, one might as well start the process over and acquire a new image because the biological parameters will have changed too much to rely on control from the delayed spatially variable application. In our experience on commercial farms, we have seen as much as 3 h per day being needed to hand carry PC cards by highly trained personnel to multiple machines spread across the landscape. Three hours is a significant percentage of the initial 24-h optimum application interval, which could be totally voided with a WLAN approach.

GAPARU personnel are also involved in developing software to facilitate the automation of the movement of information to and from the farm. One choice that was made was the use of FTP server software on the farm base computer. This software will provide secure communications to and from the farm. Remote users can easily download developed scouting maps and application maps to the base computer by providing appropriate username and password. All of the farm's operational data and information which the grower considers private will be protected from potential hackers from the outside. FTP server software (Texas Imperial Software WFTPD) provides a very secure firewall to dissuade unauthorized access to the internal system. To be able to use the base station computer as an FTP server, the DirecWay service had to be upgraded to Business Basic Service. This allows the base station to be assigned a permanent IP address, which is essential for using FTP server software. We are currently working with growers and consultants to develop automated scripts to facilitate the transfer of data from the on-farm database to the laboratory database and vice versa. This step is essential to making the technology acceptable.

7. Conclusion and discussion

The computer hardware, WLAN hardware, and software as discussed above have been deployed and tested on the Paul Good Farm in Noxubee County, MS, USA. All systems functioned within their specified published parameters. The down data rate for the DirecWay satellite Internet modem consistently ranged from 600–700 Kbps for the Residential Service. We have found that the Business Basic Service does meet and often exceeds these rates. The FHSS radio links, which cover 80% of the entire farm, delivered a user data rate of 2 Mbps. This was verified using a vehicle equipped with an FHSS radio, laptop PC, and an 8 dBi magnetically-mounted antenna on the cab of the vehicle. The entire farm was mapped with this array of equipment to determine signal availability, and the coverage pattern shown in Fig. 1 was verified. Since the base station antenna was mounted on the highest building, the radio signal could be received at any location on the farm for location of the repeater stations which performed the actual coverage for the WLAN. The farmstead was thus covered by the northwest and southwest repeater stations, such that there was no blockage of signal by any of the farm buildings, many of which were made with corrugated metal. For the 20% of the farm that was not covered by the repeater stations, the signal was blocked by the tree line from the southwest station, the area was too far away from the northwest station and the northeast station signal was blocked by terrain.

While the DSSS radios were capable of operating at 11 Mbps, the network throttled this down to the FHSS limitation of 2 Mbps to and from the base station computer. We successfully demonstrated and tested the capabilty of communicating with handheld PDAs equipped with DSSS radios. Not only could we transfer files to and from the PDAs while standing out in the field, but we could also access the Internet to any viable address. Data rates to and from the PDAs via the Internet of course were throttled to the limitations of the satellite modem which were approximately 500 Kbps down and 75–150 Kbps up, which provided a very acceptable response with minimal waits. While computer knowledgeable personnel will have not problems in moving data and information with this system, our future goal is the development of software to make the system more transparent, easier to use, intuitive for computer novices. This goal follows Moore's recommendation (Moore, 1999) to make high technology more acceptable to mainstream users.

An additional repeater station will be added to the southeast corner of the Good Farm to provide 100% coverage for the entire area. Currently 80% of the acreage is covered with three repeater stations. The northwest repeater station was moved approximately 1500 m north to provide WLAN coverage for four commercial catfish ponds in a future research effort. The Paul Good residence, the son's residence and the son-in-law's residence were provided Internet and WLAN access using DSSS point-to-point links with distances of 150, 3500, and 10,000 m, respectively, from the base station. This access provides them the capability to monitor operations remotely from their residences and to have Internet access.

Over the last two years we have successfully downloaded via the WLAN fertilizer, crop growth regulator, and pesticide application maps to the Zynx controller mounted on the appropriate farm equipment while the equipment was in the field.

An additional lesson we learned is that the crop must be considered in the design of the system. When the initial signal measurements were made, there were no crops planted, just bare soil. The grower rotates crops of soybean, corn and cotton. Corn grows much taller than the other two crops and is an excellent radio frequency absorber at 2.4 GHz. Therefore, we had to add an additional 6 m in height to each of the repeater stations to account for crop height.

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